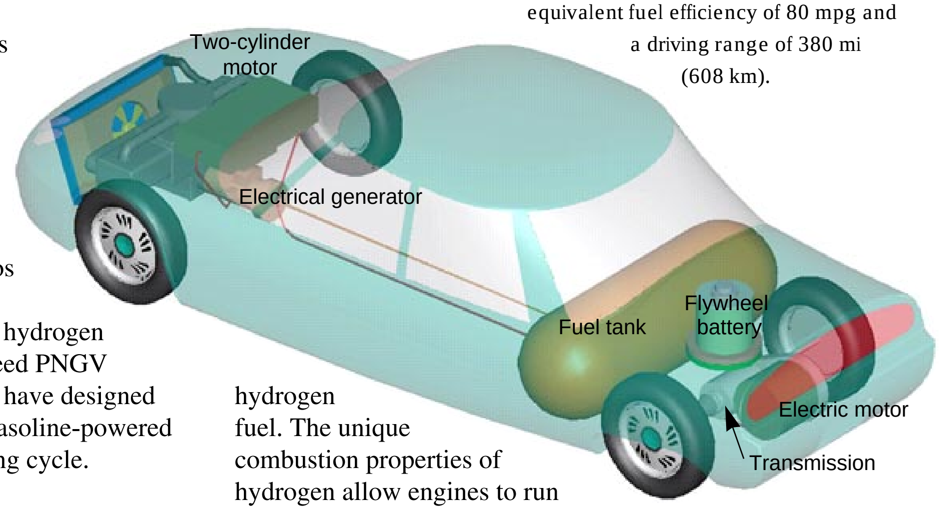
This Hybrid Vehicle Uses Hydrogen



Our conceptual design of a hydrogen hybrid vehicle features a large fuel tank for pressurized hydrogen. It has a gasoline-equivalent fuel efficiency of 80 mpg and a driving range of 380 mi (608 km).

RECENTLY, the Clinton Administration's Partnership for a New Generation of Vehicles (PNGV) set an automobile fuel efficiency goal of 80 mpg (34 km/L) to achieve responsible energy and environmental conservation. Even before the goal was announced, researchers at LLNL had joined investigators at Los Alamos National Laboratory and Sandia National Laboratories, California, to design and test a hydrogen hybrid concept vehicle that will meet or exceed PNGV guidelines. The hydrogen piston engine they have designed gets mileage equivalent to the 80 mpg of a gasoline-powered vehicle on the combined city–highway driving cycle.

Why Hydrogen Fuel?

Hydrogen has several features that make it a serious contender as an alternative fuel. It can be produced from various domestic sources, including renewable sources; it can reduce emissions to near zero while maintaining performance; and it can now be safely stored and transported. An immediate motive for moving to hydrogen is its potential to improve urban air quality. In the longer term, such a transition would also benefit the balance of payments and the energy security of the U.S. by reducing dependence on foreign oil.

Because hydrogen is a manufactured fuel, it is likely to cost more than fossil fuels for at least several decades. The cost issue means that researchers need to exploit the use of hydrogen fuel in those applications that have the highest leverage or payoff. One obvious application is in transportation. The energy efficiency of today's automobiles is only about 18%.

Despite its many advantages, hydrogen has yet to become a significant transportation fuel, even in advanced countries. Several factors hinder a transition from gasoline to hydrogen, including the absence of available vehicles with engines that can use this resource efficiently and the lack of an adequate distribution infrastructure.

Hydrogen Fuel Efficiency

Current engine designs have low energy efficiency. Small piston engines (in the range of about 40 kW or 54 horsepower) have not been optimized specifically for hydrogen fuel. The unique combustion properties of hydrogen allow engines to run leaner and at a higher compression ratio than they do with hydrocarbon fuels. Energy efficiency is a serious problem if consumers want a driving range comparable to that of today's gasoline-powered vehicles. Thus, what we need are high-efficiency drive trains if we are to consider hydrogen seriously as an alternative fuel. Researchers at LLNL are showing that such drive trains are feasible and that hydrogen has a genuine opportunity to compete for the first time in the transportation sector.

Our studies demonstrate that considerable improvement over conventional automobile efficiency can be achieved through a hybrid-electric drive train. In this concept, all the chemical energy of the fuel is converted to electrical energy by means of a piston engine coupled to an electrical generator. The electrical energy can be stored in various ways, including an advanced battery, an ultracapacitor, or an electromechanical battery (EMB), also known as a flywheel battery. Of these three technologies, the EMB is closest to full-scale demonstration. The flywheel battery, which will be the subject of a forthcoming article in *Science and Technology Review*, has an energy recovery efficiency of more than 90% and a long lifetime. Compared to the EMB, today's electrochemical batteries have an energy recovery efficiency of about 70%.

How the Hybrid Hydrogen Vehicle Works

In the hybrid concept vehicle we are developing (see the illustration), stored electrical energy is extracted as needed by the power demands for accelerating, cruising, and accessories. The engine does not idle; rather, it shuts down each time the energy-storage device is fully charged. To complete the power train, an electric motor is coupled to the wheels by a single-speed transmission. By turning the electric motor into a generator during braking, our concept vehicle includes the feature of regenerative braking. Thus, kinetic energy returns to the storage device when the brakes are applied.

If the engine/generator in a hydrogen-powered vehicle supplies enough power for a fully loaded vehicle to climb hills at cruising speeds, then it performs much like today's gasoline-powered automobiles. However, if the engine/generator supplies just enough power for average energy consumption, then it can serve as a range extender. The difference in power required for cruising versus hill climbing is about a factor of four. We are designing a fully capable concept car that can cruise and climb hills.

The Design Team's Challenges

LLNL researchers are working on the technical details of a new hydrogen piston engine with investigators at Los Alamos National Laboratory and Sandia National Laboratories, California. Essentially, LLNL is responsible for the initial system studies, engine design, and combustion kinetics. Los Alamos investigators perform the computational fluid-dynamics modeling (combustion modeling) and integrate this information into our vehicle simulation codes. Researchers at Sandia's Combustion Research Facility then do the engine-performance and emissions testing.

The need for a highly efficient vehicle and power train is driven by the associated problem of onboard storage of hydrogen fuel. Onboard fuel storage is perhaps the single most difficult task associated with our project. Table 1 shows two options we are considering for fuel storage: a cryogenic tank for liquid hydrogen or a high-pressure tank for hydrogen gas. Without increased efficiency, the onboard fuel tank would need to be about three times the volume listed in Table 1 and three times the size shown in the illustration; that is, the tank would become so large as to be impractical. We are applying the hybrid vehicle evaluation code (HVEC) developed at LLNL as a guide to select components that maximize efficiency and thus reduce fuel-tank volume and weight.

HVEC incorporates a wide range of details and complexity. The code calculates power-train dimensions, fuel economy, time to accelerate to 60 mph (96 km/h), hill-climbing performance, and emissions. Our basic premise is that we need to generate electrical energy at efficiencies of about 42%, based on a generator that is 95% efficient and an engine efficiency of about 46%.

Our calculations show that an empty vehicle weighing 2508 lb (1140 kg) (see Table 1 for additional specifications) would have a combined EPA urban/highway mileage of about 80 mpg (expressed as gasoline-equivalent fuel efficiency). Such a vehicle would require only about 10.45 lb (4.75 kg) of hydrogen for a driving range of 380 miles (608 km). For perspective, a kilogram of hydrogen has nearly the same energy content as a gallon of gasoline. Thus, our hydrogen-powered vehicle is extremely energy-efficient and has emissions equivalent to those of electric vehicles when the emissions from power plants are included. And its gasoline-equivalent fuel efficiency of 80 mpg meets the goal set by PNGV.

Table 1. Some basic specifications and calculated performance for the LLNL hydrogen hybrid vehicle.

General description	
Five-passenger, engine-flywheel hybrid vehicle	
Hydrogen internal combustion engine	
Cryogenic or pressurized hydrogen-storage system	
Principal accessory: air conditioning	
Selected vehicle characteristics	
Vehicle empty total weight	2508 lb (1140 kg)
Power-train weight	578.6 lb (263 kg)
Fuel-tank capacity	10.45 lb (4.75 kg) of hydrogen
Liquid-hydrogen tank volume @ 100 psi	28 gal (106 L)
Liquid-hydrogen tank weight @ 100 psi	79 lb (36 kg)
Pressurized-hydrogen tank volume @ 5000 psi	62 gal (235 L)
Pressurized-hydrogen tank weight @ 5000 psi	141 lb (64 kg)
Aerodynamic-drag coefficient	0.24
Rolling-friction coefficient	0.007
Electric motor	
Maximum continuous torque	100 N · m
Maximum speed motor	11,000 rpm
Transmission efficiency	95%
Hydrogen-engine efficiency	46%
Calculated performance	
Combined 55% urban, 45% highway gasoline-equivalent mileage	~80 mpg (34 km/L)
Driving range	380 mi (608 km)
Time to reach 96 km/h (60 mph)	9.7 s

With current technology, we believe that a general-purpose, low-emission, long-range vehicle that uses a hydrogen internal combustion engine is now possible. Such a vehicle could become competitive in the marketplace if hydrogen production and distribution issues are addressed. These issues are being studied at the Laboratory and will be the subjects of *Science and Technology Review* articles in the future.

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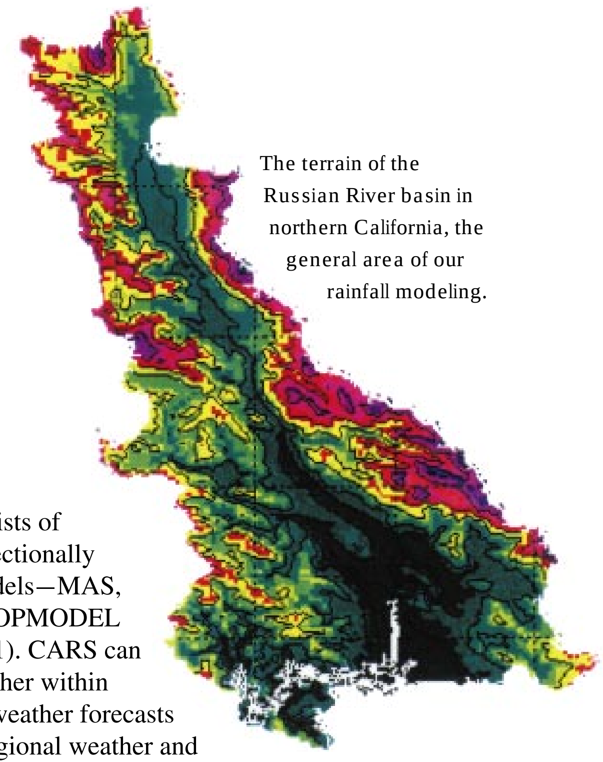
Modeling for More Accurate Weather Forecasts



The terrain of the Russian River basin in northern California, the general area of our rainfall modeling.

WEATHER is fickle, especially in the varied terrains and microclimates of the western United States. California and the other western states thrive or languish with their water supply, as the pendulum swings between drought and deluge. All too often, "average" precipitation is merely an artifact of arithmetic. Complicating the picture is the fact that the area receives its year's supply of water during the winter, and water for the dry summer must come almost entirely from reservoir storage and mountain snowpacks. At the start of each winter, everyone—water district official, fire fighter, ski resort operator, homeowner—wants to know if rainfall and snowfall will be above or below average. Accurate assessments of wintertime precipitation are particularly important for regional water management agencies as they attempt to manage reservoir capacity and balance the water demands of agricultural, industrial, urban, recreational, and environmental interests. In addition, since water supply is a limiting factor for urban and industrial development, regional planners are increasingly concerned about the effect of global climate change on local water resources.

Numerical simulation using general circulation models (GCMs) is one of the most important tools for understanding global climate and for projecting long-term climate change. Great strides have been made in recent years to couple models of atmospheric, terrestrial, and oceanic processes to provide more complete climate simulations. However, because of their coarse spatial resolution (typically 100 km), it is difficult to apply these GCMs directly to regional forecasts. In California, for example, precipitation is closely related to topographic features (e.g., the Coastal Range, the San Francisco Bay) with spatial scales of less than 100 km, too small to be resolved by a GCM. Increasing the resolution of the GCMs to provide regional simulations is beyond the capabilities of present and envisioned computational resources.

Mesoscale models, nested within GCMs, are being developed to assess regional climate. As part of an effort to investigate regional-scale atmospheric flow, precipitation, and hydrology over various time scales and spatial resolutions, four LLNL researchers—Jinwon Kim, Norman Miller, Donald Ermak, and William Dannevik—have developed the Coupled Atmosphere-Riverflow Simulation (CARS) system. The system consists of three unidirectionally coupled models—MAS, LAS, and TOPMODEL (see Figure 1). CARS can be nested either within large-scale weather forecasts to predict regional weather and river flow or within global climate analysis data to assess regional climate and long-term water resources.

The Mesoscale Atmospheric Simulation (MAS) model was developed jointly by LLNL and the University of California at Davis.[1] It models atmospheric processes, including those involved in storms, from which it computes local precipitation, wind velocity, and other atmospheric variables. MAS computes rainfall and snowfall separately (using a bulk cloud microphysics scheme[2]), an important capability because mountain snowpacks are major sources of summertime water for the western states.

The Land Analysis System (LAS) is a system of codes taken in part from software developed by the U.S. Geological Survey[3] and combined with numerous other codes and scripts developed at LLNL. It provides land surface characteristics (such as flow directions, topographic slopes, water channels, and hydrological characteristics) for individual watersheds, based on digital elevation data provided by LLNL's Atmospheric Release Advisory Capability group. The areas and locations of the LAS watersheds are nested within the grid points of the MAS model.

TOPMODEL is a hydrology model, developed originally in 1979 at Lancaster University, England,[4] and enhanced and expanded over the years. LLNL's version of TOPMODEL takes the watershed-averaged precipitation and atmospheric variables from MAS together with the land surface characteristics from LAS to simulate surface and subsurface hydrology and river flow for individual watersheds.

The series of storms that struck Northern California in January 1995 provided an effective test of CARS's ability to make accurate short-term forecasts of precipitation and flooding. Between January 7 and January 11, three strong storms hit California. Several areas experienced extensive flooding as soils became saturated after the second and third storms came ashore. The Russian River basin was among the hardest-hit areas, with an estimated $800 million in flood-related damage.

Large-scale forecast data (80-km resolution) from the National Weather Service were used as input to the CARS system, and MAS simulations (20-km resolution) were run producing precipitation fields for all of California for this time period. MAS's ability to calculate rainfall and snowfall separately was essential for predictions of river flow, since snowfall does not immediately affect river flow.

California's complex terrain can cause considerable differences in the precipitation received by areas only a few miles apart. As a result, accurate estimates of local precipitation are essential for accurate estimates of river flow in mountainous areas. To illustrate this dependence, CARS computations were made for the area-averaged daily rainfall for the entire Russian River basin (approximately 7000 km^2) and compared with calculations of the Hopland watershed (a smaller area, about 660 km^2) within the Russian River basin, north of the Hopland gauge station. The simulated daily rainfall for the two areas differs by factors of two to three (Figure 2a).

To evaluate CARS's ability to predict river flow and flooding, simulated precipitation values for the Hopland watershed were compared with the observed precipitation values for the first 12 days of January (which were used by the National Weather Service's California–Nevada River Forecast Center to model river flow). CARS successfully simulated the amounts and timing of rainfall over the Hopland watershed, except on January 10, where the model overestimated precipitation by a factor of two (Figure 2b). Upon further examination, this overestimation was found to have resulted from excessive amounts of water vapor flux in the input data for the CARS simulation, clearly demonstrating the dependence of regional predictions on accurate large-scale data.

Figure 2c plots the observed and simulated daily-mean river flow volume of the Russian River at the Hopland gauge station from January 1 through January 12. CARS simulated the river flow rate to within 10% accuracy during the flood stage. The overestimation of modeled river flow for January 11 was due in part to the overpredicted rainfall for January 10, as noted above. For the low flow periods before flooding, simulated river flow exceeded the observed river flow mainly because of uncertainties in the initial water content of the soils, a difficult variable to simulate.

These successful predictions of extreme precipitation and river flow demonstrate the applicability of the CARS system to short-term, local weather forecasting. Such modeling will not replace human weather forecasters; rather, modeling can provide another type of data to assist forecasters. As Jinwon Kim, one of CARS's developers, remarks, "The value of front-line forecasting is that the forecasters have the experience to interpret data from various sources. Our goal is to create a modeling system that can help improve the accuracy of a forecast and the time span for which it is valid."

Improving short-term weather forecasts is but one step toward the long-range goal of understanding and predicting global climate change and its regional impacts. Having successfully simulated the Russian River situation, CARS's developers are moving ahead on several fronts.

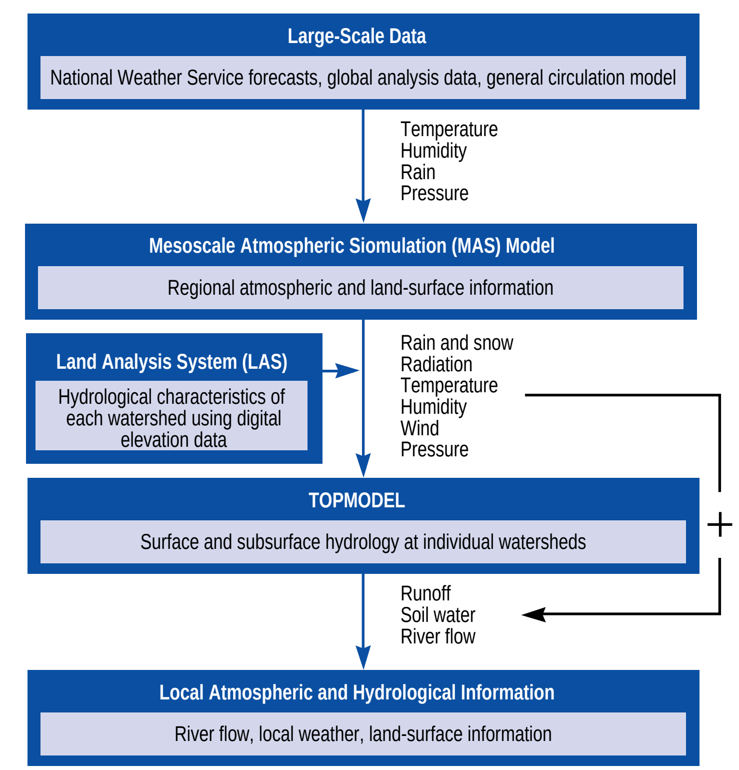


Figure 1. The CARS system. The MAS model takes large-scale input data and telescopes it down to simulate local precipitation and atmospheric variables, which are then averaged over individual watershed areas (obtained from LAS). LAS also computes topographic characteristics for the watersheds. TOPMODEL uses the precipitation and atmospheric variables simulated by MAS together with the land surface properties determined by LAS to compute river flow and hydrology for the specific watersheds.

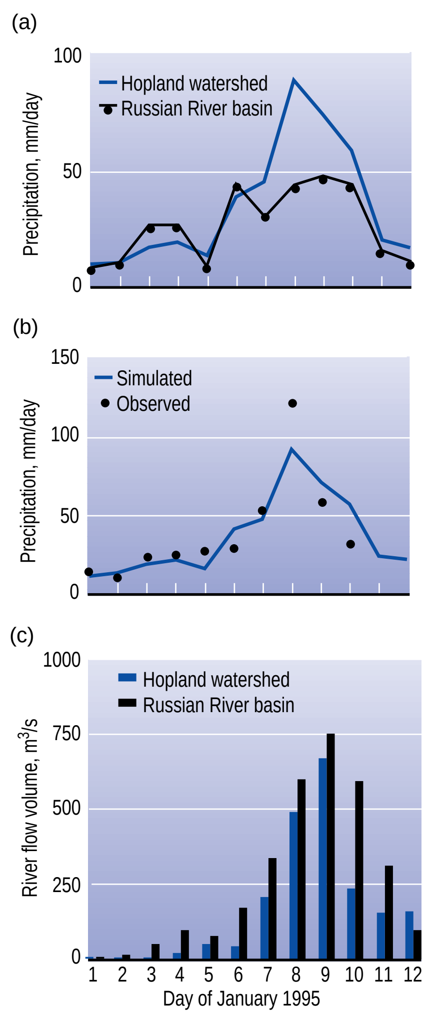


Figure 2. (a) Simulated precipitation for the entire Russian River basin and for the Hopland watershed. (b) Observed and simulated precipitation for the Hopland watershed of the Russian River basin. (c) Observed and simulated river flow at the Hopland gauge station on the Russian River. The CARS simulations are in generally good agreement with observed precipitation and river flow, the discrepancies (overestimations) arising in large part from inaccuracies in the large-scale input data.

CARS's hydrology simulation model is being extended to include other major river systems in California, specifically the inflow to Lake Shasta, the Feather River, and the American River. This expansion will make it possible to use CARS for simulating local weather and river flows over northern California's major watersheds.

In collaboration with the National Weather Service, the CARS system is being used for experimental weather prediction for the southwestern United States. Simulations are also being run to test CARS's ability to assess water resources over seasonal, multiyear, and decadal time scales, to model the effect of such global phenomena as El Niño on regional climate, and to determine the effects of pollutants such as carbon dioxide and aerosols on climate change.

References

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4. K. J. Beven and M. J. Kirkby, "A Physically Based, Variable Contributing Area Model of Basin Hydrology," *Hydrological Science Bulletin* **24**, 43–69 (1979).

To view this article with interactive links to these references, visit our Internet homepage at *http://www.llnl.gov/str/str.html*. After August 1, click on references in color for immediate access to additional specific information.

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Patents and Awards

Each month in this space we report on the patents issued to and the awards received by Laboratory employees. Our goal is to showcase the distinguished scientific and technical achievements of our employees as well as to indicate the scale and scope of the work done at the Laboratory.

Patents

Patent issued to	Patent title, number, and date of issue	Summary of disclosure
Anthony M. McCarthy	"Method for Forming Silicon on a Glass Substrate" U.S. Patent 5,395,481 Issued March 7, 1995	A method by which single-crystal silicon microelectronics may be fabricated on glass substrates at low temperatures.
Michael W. Droege, Paul R. Coronado, and Lucy M. Hair	"Method for Making Monolithic Metal Oxide Aerogels" U.S. Patent 5,395,805 Issued March 7, 1995	A method in which a metal alkoxide solution and a catalyst solution are prepared separately and reacted to produce transparent, monolithic metal oxide aerogels of varying densities.
Earl R. Ault and Terry W. Alger	"Metal Vapor Laser Including Hot Electrodes and Integral Wick" U.S. Patent 5,396,513 Issued March 7, 1995	A specifically designed electrode and wicking associated with the plasma tube of metal vapor lasers.
Anthony M. McCarthy	"Method of Forming Crystalline Silicon Devices on Glass" U.S. Patent 5,399,231 Issued March 21, 1995	A method for fabricating single-crystal silicon microelectronic components on a silicon substrate and transferring them to a glass substrate.
Thomas C. Kuklo	"Kinematic High Bandwidth Mirror Mount" U.S. Patent 5,400,184 Issued March 21, 1995	An adjustable high bandwidth mount for mirrors used in optical systems. The mount is adjustable along two perpendicular axes.
Steven T. Mayer, James L. Kaschmitter, and Richard W. Pekala	"Aquagel Electrode Separator for Use in Batteries and Supercapacitors" U.S. Patent 5,402,306 Issued March 28, 1995.	An electrode separator formed of aquagel with electrolyte in its pores for electrochemical energy storage devices.

Awards

Dana Isherwood, the Laboratory's legislative analyst, and **Dick Post**, a Laboratory Associate in the Energy Directorate, were elected fellows of the **American Association for the Advancement of Science (AAAS)** in recognition of their scientifically or socially distinguished efforts on behalf of the advancement of science or its applications.

Ralph Jacobs, director of New Technology Initiatives in the Laser Program at LLNL, was elected fellow of the **American Physical Society**. He was honored for "fundamental and applied contributions to the research and development for a wide variety of gaseous, solid, and liquid laser media."

Tom McEwan and his "radar on a chip" were honored in April by the **Federal Laboratory Consortium** for excellence in transferring technology from a laboratory to private business. The Consortium is an association of Department of Energy research facilities that assists the U.S. public and private sectors in using technologies developed by federal research laboratories.

Secretary of Energy Hazel O'Leary presented Laboratory representatives with the **Management and Operation Contractor of the Year Award** on March 31 in recognition of its outstanding achievement in providing substantial contracting opportunities for small businesses. She cited our socioeconomic program assisting small, women- and minority-owned business in securing procurement contracts with the Laboratory as the best of its kind in the DOE complex.

The 1994 **E. O. Lawrence Award** has been awarded to **Michael Campbell**, head of the Laboratory's lasers program, and **John Lindl**, scientific director for Inertial Confinement Fusion for distinguished leadership in helping to propel laser-driven inertial confinement fusion to the forefront of physics research. The award was established in 1959 in memory of Ernest O. Lawrence to recognize outstanding contributions in the field of atomic energy. Dr. Campbell was also the winner of the 1995 **Edward Teller Medal**. This award was established in 1989 to commemorate Teller's contributions to fusion energy.

The **Northern California Section of the American Institute of Chemical Engineers** has named a hazardous explosives cleanup process developed at the Laboratory as **Project of the Year**. The award cited the project's principal investigators **Ravi Upadhye, Bruce Watkins, Cesar Pruneda, and Bill Brummond**. The process uses molten salt to safely dispose of waste explosives and explosive-like materials.